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## Disclaimer

# Test station development for laser-induced optical damage performance of broadband multilayer dielectric coatings

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## ABSTRACT

Laser-induced damage threshold (LIDT) testing was performed on commercially-available multilayer dielectric coatings to qualify for use in the High Repetition-Rate Advanced Petawatt Laser System (HAPLS) for Extreme Light Infrastructure Beamlines. Various tests were performed with uncompressed pulses (150 ps) from a 780 nm-centered Ti:Sapphire regenerative amplifier, and the raster scan method was used to determine the best-performing coatings. Performance varied from 2-8 J/cm$^2$ across samples from 6 different manufacturers.

**Keywords:** Need to choose some Keywords

## 1. INTRODUCTION

The High Repetition-Rate Advanced Petawatt Laser System (HAPLS) is currently being developed by Lawrence Livermore National Laboratory (LLNL) for ELI-Beamlines in Czech Republic. HAPLS is a Ti:Sapphire-based, ultrafast, chirped-pulse amplified laser, designed to produce 1 PW peak power at 10 Hz repetition rate by delivering 30 J per pulse in a 30 fs pulse duration. As is typical in petawatt-class or other high-intensity laser systems,[1] a major design limitation of the system is the laser-induced damage threshold (LIDT) of its optical elements. Therefore, a critical step in the development process is not only a careful choice of optics, but also a performance verification and validation through LIDT testing.

In the case of HAPLS, the desired fluence performance of mirrors in its amplifiers is 10 J/cm$^2$ at a stretched pulse duration of 1 ns. Multilayer dielectric (MLD) optical coatings are the obvious choice, since they are well known to have superior LIDT-performance to other broadband options such as metallic mirrors, while still providing favorable optical properties such as $> 99\%$ reflectivity across several 10's of nm bandwidth. However, MLD coatings have widely-varying LIDT based on design and production considerations. Particularly, the presence of surface defects in the coating or substrate can lead to a drastic lowering of LIDT locally (by even as much as an order of magnitude), which may often cause catastrophic damage growth and subsequent failure of the optic. Since in application the laser beam will illuminate a relatively large area of the optic, it will be likely to encounter such defects, and therefore the testing protocol should also measure a large area of the optic. The primary test performed in this work, raster scanning, is a technique which accomplishes this large area LIDT testing, where the focused test beam is scanned across a large area of the optic. In this work, we present an LIDT testing methodology (primarily raster scanning) and results for commercially-available broadband high-reflectors (BBHRs).

## 2. EXPERIMENT

A test station was developed at OSU in collaboration with LLNL for LIDT determination in air. The MLD coating types tested were commercially available BBHRs at 800 nm at the three typical mirror angles of incidence: 0°, 45°S-, and 45°P-polarization. Various tests were performed, including both small and large test areas (R-on-1, S-on-1, and the National Ignition Facility raster scan protocols), though the main goal was successful raster scanning at the target fluence. High resolution *in-situ* damage detection and offline pre- and post-test large area surveys (1 µm resolution) were used to examine the test sites. "Passing" a test was defined as no damage initiations, and the highest passing fluence is reported.

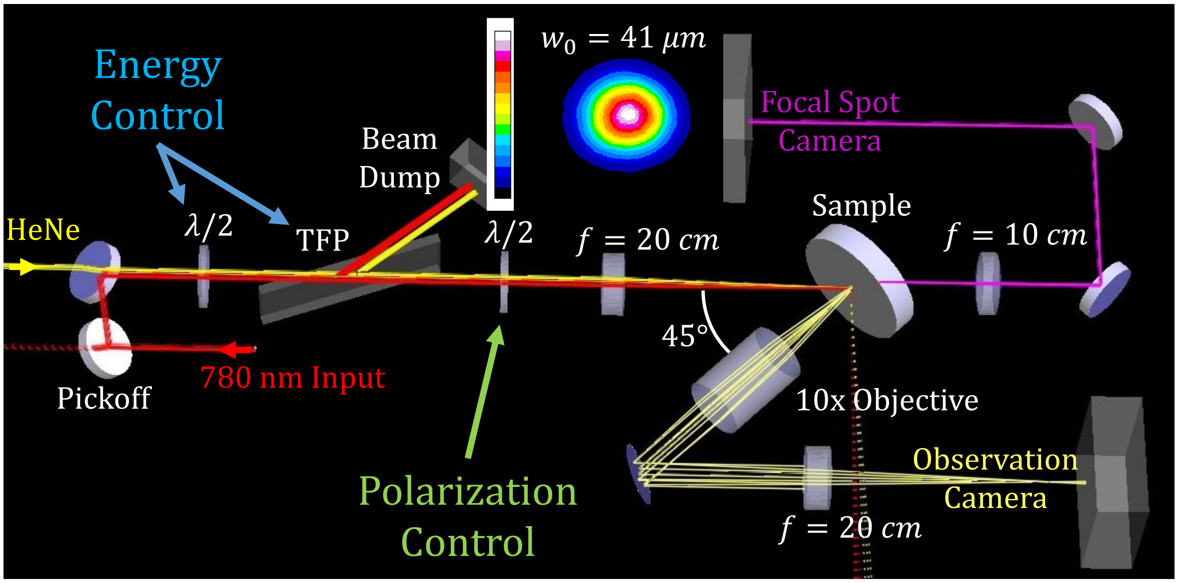


Figure 1. Schematic of the test station. Test fluence and polarization controlled by waveplates and a thin-film polarizer. The observation camera views the sample for alignment and during testing under illumination of HeNe laser. The focal spot camera profiles the beam when the sample is removed (beam profile shown).

The test station uses uncompressed pulses from the liquid-nitrogen-cooled regenerative amplifier of a Ti:sapphire-based CPA laser system (OSU, GRAY Laser), which has laser wavelength $\lambda = 780\,\mathrm{nm}$, FWHM bandwidth 35 nm (wavelength and bandwidth variable via intracavity etalon), repetition rate $\leq 500\,\mathrm{Hz}$ (variable via an external Pockels cell and polarizer), pulse energy $E \leq 5\,\mathrm{mJ}$ with RMS stability $< 2\%$, and pulse duration $\tau_{test} = 150\,\mathrm{ps}$. Since this 150 ps test pulse is shorter than the HAPLS 1 ns stretched pulse, we applied an empirical pulsewidth scaling law valid for 1053 nm, ns pulses:[2]

$$F_{HAPLS} = F_{test}\left(\frac{\tau_{HAPLS}}{\tau_{test}}\right)^{0.35} = 1.94F_{test} \approx 2F_{test} \tag{1}$$

where $F$ is the LIDT fluence. While we used this scaling law to give an estimation of LIDT fluence in HAPLS conditions, we acknowledge that the theoretical pulsewidth scaling in the sub-ns regime is not well understood.[3] However, we note that this is a more conservative estimate than using a simple heat diffusion scaling law ($\propto \tau^{1/2}$). The fluence values reported in this paper are the actual tested fluence values (at 150 ps), and for the purposes of this paper we will henceforth focus on the testing and not on validation of this pulsewidth scaling.

Fig 1 shows a schematic of the test station. The pulse is first reduced by more than an order of magnitude via a pickoff (coarsely variable as needed), and energy is further controlled via a broadband $\lambda/2$ waveplate and polarizer combination. In the primary configuration, the test fluence was variable up to $9\,\mathrm{J/cm^2}$, though secondary tests were available with up to $20\times$ fluence. The test (linear) polarization angle is controlled by a second $\lambda/2$ waveplate. A $f = 20\,\mathrm{cm}$ air-spaced achromatic lens focuses the laser onto the target with a beam waist radius $w_0 = 41\,\mu\mathrm{m}$, where the beam profile is measured with the sample removed by imaging the focal spot onto a CCD. During the experiment, a co-propagating HeNe alignment laser illuminates the sample test area, and a 10x infinity-corrected objective gathers scattered HeNe light onto a second camera to provide *in-situ* damage detection and observation as well as providing a consistent $\pm 4\,\mu\mathrm{m}$ sample alignment. The uncertainty in $w_0$ is further minimized by the $f/\# \approx 87$ focusing geometry with a corresponding Rayleigh range $z_R \approx 7\,\mathrm{mm}$. The sample mount has 5 degrees of freedom (not shown), where the translations along the sample plane are controlled electronically for scans up to 5 cm-long with $2.5\,\mu\mathrm{m}$ stepwise resolution. With this setup, three types of tests were performed: R-on-1, S-on-1, and raster scans.

R-on-1 testing ramps the fluence at a single site, which gives LIDT information intrinsic to coating design, but is limited by small test area ($\approx 10^{-4}\mathrm{cm}^2$ in this case). For high-quality coatings (with low defect densities)

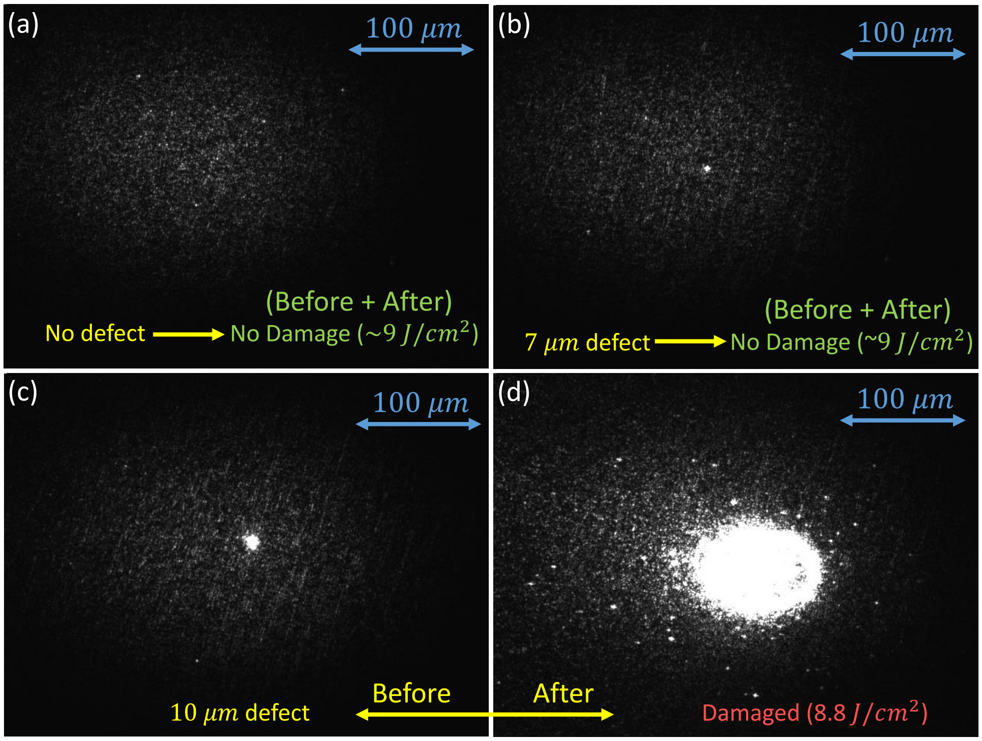


Figure 2. A series of R-on-1 test sites imaged by *in-situ* camera. (a) and (b) show two sites which remained undamaged after a ramp to 9 J/cm$^2$, where (a) is a typical surface quality and (b) has a $\approx$ 7 µm pre-existing defect. (c) shows a site with a $\approx$ 10 µm pre-existing defect which did damage at $\leq$ 8.8 µm, where the resultant crater is shown in (d). This variability of LIDT with respect to defects makes R-on-1 an unsuitable method for performance qualification.

R-on-1 tests will be unlikely to encounter sparse defects, and therefore this test indicates only an upper-bound of LIDT performance. This variability due to defects can be seen in Fig. 2, where some example test sites are shown from the *in-situ* camera. There are many weak scattering sites visible with very high number density which perhaps influence the coating's intrinsic LIDT, but we considered this to be a pristine or typical area. In Figs. 2a-b, both the pristine surface and the $\approx$ 7 µm defect resulted in no damage up to 9 J/cm$^2$ (max fluence in primary configuration). However in the case of Fig. 2c, the "before" image shows a 10 µm defect which did result in damage at $\leq$ 8.8 J/cm$^2$. Furthermore, this sample went on to fail the raster scan as low as 3.5 J/cm$^2$.

At 5 J/cm$^2$ (the desired test fluence after pulsewidth scaling of LIDT), an additional S-on-1 accelerated lifetime test was performed (> 30000-on-1) at 500 Hz on pristine sites to simulate long term operation of a 10 Hz laser system. These lifetime tests did not result in catastrophic damage. However in the scope of this performance qualification work, the LIDT lower bound is more important than the intrinsic behavior, so R/S-on-1 tests were performed only in limited cases in favor of raster scanning.

As has been mentioned thus far, the primary testing performed for this work was raster scanning in order to provide large area coverage at the test fluence to increase the probability of sampling LIDT-lowering defect sites. To meet the HAPLS desired fluence (and considering pulsewidth scaling), the "goal test" was to raster a 1 cm$^2$ area at 5 J/cm$^2$ with no damage initiations. The serpentine raster scan parameters were 8 mm/s (y-axis active) at 500 Hz, with a row advancement of 15 µm. This results in the fluence map shown in Fig. 3, with 58% area coverage at 90% peak fluence and 99% coverage at 80% peak fluence. However, stage hardware upgrade was necessary to provide this scan speed, so the tests were completed in two steps: 1) "reduced-area tests" (before upgrade), 2) "goal tests" (after upgrade).

Reduced-area tests covered 0.1 cm$^2$, due to initial stage limitations (2 mm/s scan speed and overheating). An example of one such test is shown in Fig. 4, where the underlying image is a 1 µm-resolution post-microscopy scan, and the blue/red rectangles correspond to the raster areas of lower/higher fluences. Testing began at the

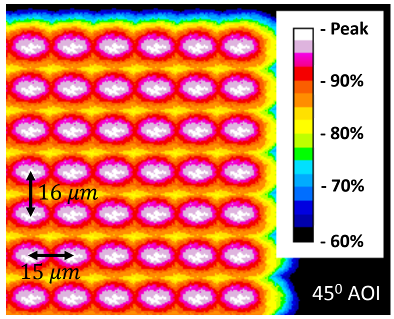


Figure 3. Map of maximum test fluence versus location (zoomed in on a subsection) for the goal test, depicting the scan parameters 8 mm/s at 500 Hz.

lowest fluence (0.5 J/cm$^2$), and if no damage was detected via *in-situ* microscope then the test proceeded to the next fluence steps (2, 3.5, 5 J/cm$^2$). If damage was detected in-situ, then no higher fluences were tested. Note that fluences were ramped over the same area to allow laser conditioning if applicable. The Figs. 4b-c also show zoom-ins of two very different damage sites from the scan, where the difference is a result of exposure variation in the typical scanning area versus the row advancement step at the edge. Due to an internal delay time of the controller when switching between stages of $\approx 100$ ms during row advancement, the endpoints of each raster line were exposed to $\approx 50$ pulses, and if a defect was encountered, the damage was greatly exaggerated due to growth (as in Fig. 4c).

## 3. RESULTS

The results of the reduced-area raster scans are summarized in Fig. 5, and we recall that the desired passing fluence for the test pulsewidth was 5 J/cm$^2$. Manufacturers (each letter represents a unique manufacturer) were not required to provide their coating details, though Mfr. B did indicate two types of coatings: hafnia/silica (B1) and tantala/silica (B2). All samples passed 2 J/cm$^2$, but samples from 4/6 manufacturers failed at 3.5 J/cm$^2$. Fig. 6 shows an example of one of these failed rasters. In some cases the debris generated from one damage site influenced further damage sites, but this was not a concern for this work since "passing" the test required zero damage initiations. There was no attempt made to quantify the defect density.

With the reduced-area testing complete, samples from Mfr. B were selected for a larger area raster scan ("goal test" above). Fig. 7 shows a stitched microscopy scan of sample B1-45°S, which was found to pass the goal test. Upon comparison of the offline pre- versus post-microscopy scan, the only changes to the surface were a few visible pre-existing defects which appeared darkened in the post-microscopy, but did not grow significantly (shown in 7b-c).

## 4. CONCLUSION

A test station was developed to evaluate optical damage performance (over large areas) of commercially available BBHR coatings for use in chirped-pulse amplifiers. Raster Scans identified samples supplied by Mfr. B to meet the target fluence 10 J/cm$^2$ at 1 ns (5 J/cm$^2$ at 150 fs) for all 3 mirror angles of incidence (45°S, 45°P, 0°), and verified performance over 1 cm$^2$ area. Future work with this test station include Thin Film LIDT Competition 2015 at SPIE Laser Damage Symposium,[4] as well as further testing for HAPLS with larger bandwidth and vacuum environment, to more closely simulate HAPLS operational parameters.

## ACKNOWLEDGMENTS

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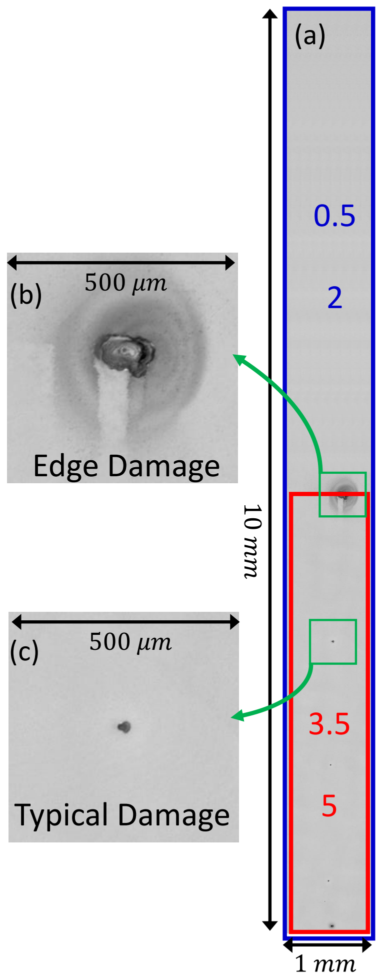


Figure 4. Post-microscopy of an example reduced-area raster scan (45°S, Mfr. F). The blue and red rectangles in (a) indicate raster scanned regions of lower (0.5, 2 $\mathrm{J/cm^2}$) and higher (3.5, 5 $\mathrm{J/cm^2}$)fluence respectively. (b) and (c) are zoom-ins of two damage sites at 3.5 $\mathrm{J/cm^2}$, where (b) has undergone catastrophic growth due to increased exposure during the row advancement step of the raster scan. (c) represents a more typical damage site.

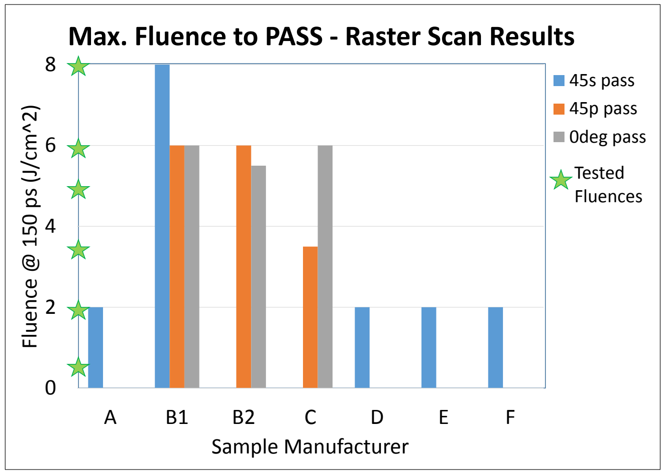


Figure 5. Summary of LIDT results from raster scanning, where each letter indicates a unique manufacturer. Recalling that the desired fluence is $5\,\mathrm{J/cm^2}$ taking into consideration the pulsewidth scaling, Mfr. B/C met all/some of the requirements of this testing.

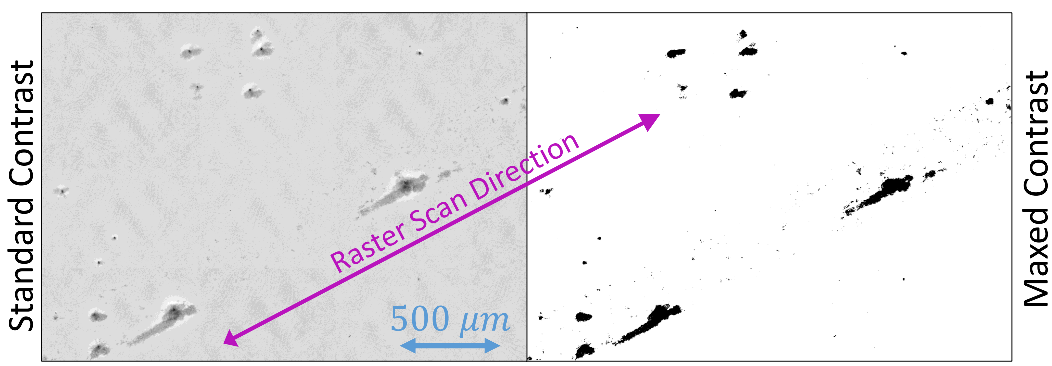


Figure 6. Example of a raster scan which obviously damaged at $3.5\,\mathrm{J/cm^2}$ (45°S, Mfr. A). Some correlation is visible between the damage pattern and the scan direction, indicating that debris from some damage sites influenced further damage initiation or growth. A maximum-contrast replica of the image is also included to emphasize the presence of the many less-obvious damage sites, and de-emphasize the image noise.

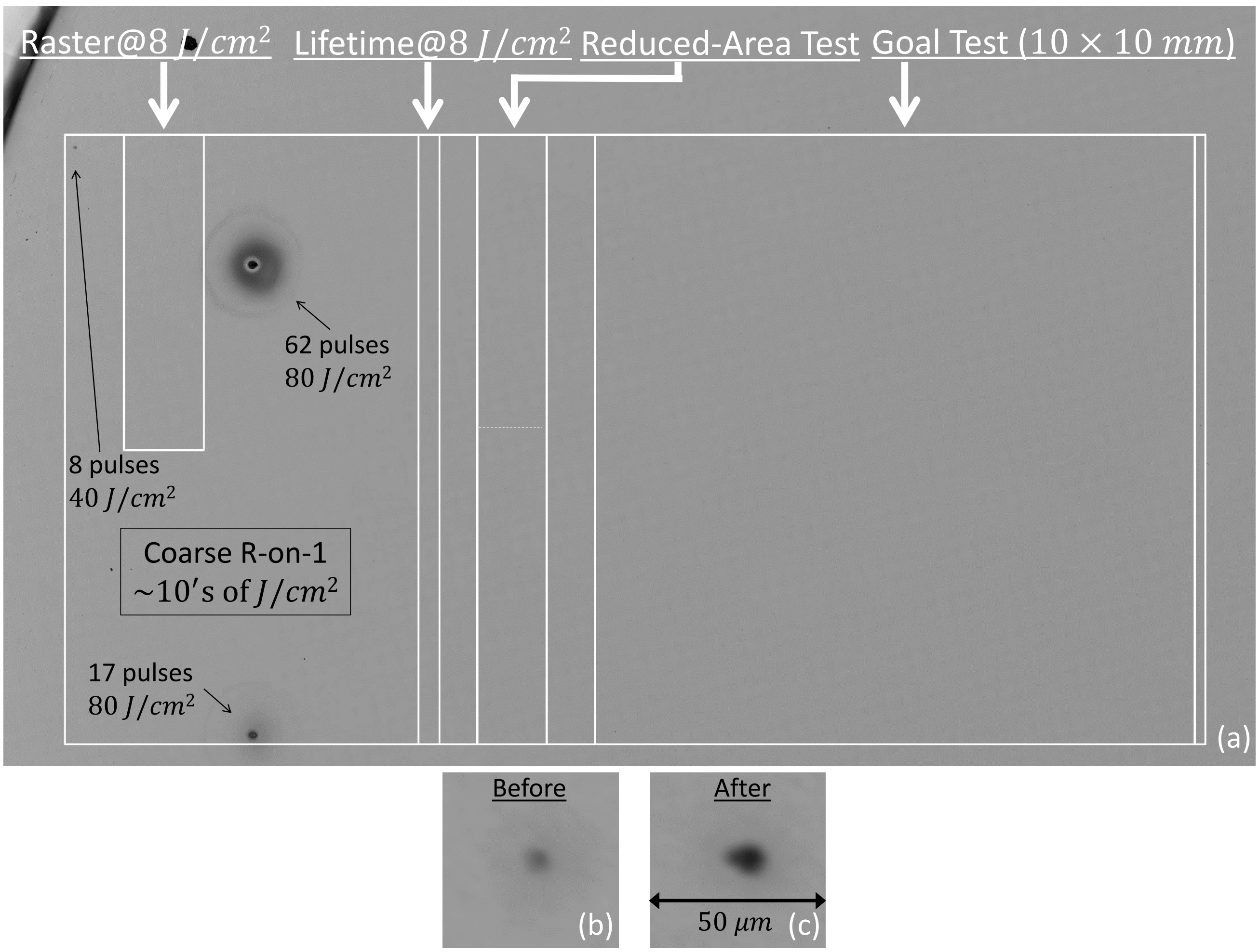


Figure 7. Offline post-microscopy scan, showing all relevant areas tested in sample B1-45°S. The scan is relatively plain, as this sample exhibited almost no failure. The only measurable change in the whole goal test region was the darkening of a few pre-existing defects, though we judged this as a "pass" since the defects did not grow significantly - these pre-/post-scans of an example defect is shown in (b) and (c).

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